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Citation for published version:
Foteinis, S 2022, 'Wave energy converters in low energy seas: Current state and opportunities', *Renewable and Sustainable Energy Reviews*, vol. 162, 112448. https://doi.org/10.1016/j.rser.2022.112448

Digital Object Identifier (DOI):
10.1016/j.rser.2022.112448

Link:
Link to publication record in Heriot-Watt Research Portal

Document Version:
Publisher's PDF, also known as Version of record

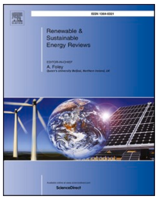
Published In:
Renewable and Sustainable Energy Reviews

Renewable and Sustainable Energy Reviews 162 (2022) 112448

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser



Wave energy converters in low energy seas: Current state and opportunities

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A R T I C L E I N F O

Keywords:
Marine renewable energy
Wave power
Ports and harbour breakwaters
Electricity intermittency
Decarbonisation
Shore power

A B S T R A C T

Existing wave energy technology has been designed for ocean waves, which, however, shorten the lifespan of wave energy converters and mooring systems. Furthermore, commissioning and maintenance in the harsh ocean conditions are challenging and expensive. For wave energy technology to realise its full potential and become commercially attractive, smaller, more economical, and resilient converters should be first introduced, tested, and optimized, as was the case with wind energy. Low energy seas such as the Mediterranean, Baltic, Caspian, Black, and Red Sea are ideal for this purpose. However, the body of knowledge on wave energy converters is limited and primarily focuses on the Mediterranean. Low capacity factors have been reported, which suggests that existing technology should be downscaled to fit the milder wave regimes. Climate change tends to increase the wave energy resource, which could be beneficial for wave energy harnessing, however, will greatly affect beach and coastal erosion and ports functionality. Converters in the nearshore can protect ports and the coast and mitigate erosion. Other secondary functions include desalination, hydrogen production, pumped-storage hydroelectricity, photovoltaic panel integration, and wave-wind farms co-location. Even though wave energy converters can counter beach erosion, they might also negatively affect aquatic ecosystems through vibrations and low-frequency long-duration noise, but little attention has been paid to their environmental impacts. Overall, wave energy can increase renewable energy penetration, decarbonize power generation, and promote job creation, and low energy seas can play an important role in advancing existing technology and help the industry progress.

1. Background

Wave energy is a renewable energy source with vast potential that remains largely unexploited. Sea waves offer a high energy density, good forecasting, and less variability than wind energy [1]. This is because the initially wind-driven waves propagate far beyond the geographical extent of the original storm where they were generated, and last longer, as waves disperse. However, even though wave energy could improve renewable energy penetration and mitigate intermittency, the industry is nascent and has lagged decades behind established renewables such as wind and solar [2,3]. Today, many different wave energy converter (WEC) technologies exist, with over a thousand ideas being already patented [4], but none sufficiently mature for commercialisation [3]. Underlying reasons include technological constraints, high capital expenditures (CAPEX), and unsuccessful series of development projects, which all translate to high risk for investors.

Existing technology has been designed for ocean waves, where high power levels (in some instances well over 60 kW/m [1]) dictate that WECs should be large and bulky to withstand waves and weather extremes. At first sight, high power levels appear promising for wave energy harnessing. However, in high-energy storms WECs enter survivability mode and do not generate power, their lifespan reduces, while commissioning and maintenance in the harsh ocean conditions tend to be difficult and expensive. As a result, the levelized cost of electricity (LCOE) for wave energy is high [3,5]. However, as the technology matures cost will reduce, e.g., the CAPEX of a WEC from research and development (R&D) to prototype to commercial stage reduces by 33% and 62% respectively [6].

To reduce cost, smaller, more versatile, and resilient WECs, which are easier to moor and maintain, should be first introduced, tested, and optimized, before the industry progresses to sustainable and viable large devices. Low energy seas comprise ideal places to employ relatively small-scale converters. In these water bodies, the low fetch lengths (defined as the distance to the next mass land) prevent the development of waves as large as in the oceans. As a result, the annual mean wave power (P_{mean}) in low energy seas ranges from 2 to 12 kW/m in the Mediterranean [7] (average 3 kW/m) [8]; 1.5–5.2 kW/m in Baltic [9] (average 4 kW/m) [8]; 5–14 kW/m in Caspian [10]; 2–10 kW/m in Black Sea [11] (average 3 kW/m [8]); and 2–4.5 kW/m in the most

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https://doi.org/10.1016/j.rser.2022.112448
Received 24 September 2021; Received in revised form 27 February 2022; Accepted 4 April 2022

Nomenclature

List of abbreviations/acronyms

AWS	Archimedes Waveswing
CAPEX	Capital expenditure
CF	Capacity factor
DEIM	Department of energy, information engineering and mathematical models
EEZ	exclusive economic zone
GOW	global ocean wave
HSST	Hexagonal slope shaped torus
ISWEC	Inertial sea wave energy converter
LCOE	Levelised cost of electricity
LCA	Life cycle assessment
LCIA	Life cycle impact assessment
LCI	Life cycle inventory
LFM	longitudinal-flux permanent-magnet machine
MGR	Mechanical gear rectifier
MSL:	Mean sea level
O&M	Operation and maintenance
OBREC	Overtopping breakwater for energy conversion
OE Buoy	Ocean energy buoy
OTD	Overtopping device
OWC	Oscillating water column
OWSC	Oscillating wave surge converter
PB3	PowerBuoy 3
PeWEC	Pendulum wave energy converter
PIVOT	Pivoting buoy wave energy system
PMG	Permanent magnet generator
POC	Proof of concept
PSH	Pumped-storage hydroelectricity
R&D	Research and development
REWEC3	Resonant wave energy converter 3
SEAREV	Système Électrique Autonome de Récupération d'Énergie des Vagues
SSG	Sea-wave slot-cone generator
SWAN	Simulating wave nearshore
TRL:	Technology readiness level
U-OWC	U-shaped oscillating water column
WAM	Wave model
WEC	Wave energy converter
WESA	Wave energy for a sustainable archipelago

List of symbols/notations

Hs	Significant wave height
$\mathbf{P_{mean}}$	Mean wave power
Te	Energy period

List of units

CO2eq	Carbon dioxide equivalent
g	Gram
GWh	Gigawatt hours
kW	Kilowatt
m	Metre
MW	Megawatt
s	Second

energetic areas (central and northern) of the Red Sea [12].

Low P_{mean} values might appear counterintuitive for wave energy harnessing; however, smaller waves present certain key advantages. WEC design loads are reduced, survivability is increased, and emplacement, commissioning, and maintenance are simpler, safer, and less costly compared to the ocean [1,13]. Furthermore, in low energy seas wave energy's annual variation is, in general, lower than that of the oceans [14,15], while the low tidal range [1,16] is also beneficial for WEC emplacement and operation and maintenance (O&M).

Antecedent to the recent ventures of directly emplacing large-scale WECs in high energy waters (oceans), this was not the case for wind energy which matured through the introduction and testing of small (<10 kW) and medium (<100 kW) devices [17,18], before maturing and progressing to wind turbines as high 7 MW in the onshore and even higher in the offshore [19]. Therefore, it is suggested that the wave energy industry could follow a similar pathway, whereby small and medium scale WECs would be introduced and tested before sustainably progressing to viable large-scale WECs. In this regard, low energy seas can play an important role, however, up to now the state-of-the-art and the opportunities for WEC emplacement in such areas has not been comprehensively reviewed. Considering these challenges, the body of knowledge on WEC emplacement in five enclosed or semi-enclosed low energy seas, i.e., Mediterranean, Baltic, Caspian, Black and Red Sea, is critically reviewed and discussed. The main objectives are to identify opportunities for tailoring existing technology to milder wave regimes, propose avenues to make wave energy harnessing commercially attractive for such areas, and provide insight for the sustainable emplacement of wave energy technology in low energy seas and beyond, which can increase renewable energy penetration, help decarbonize the electricity grid, and promote job creation. The state-of-the-art state for each examined sea, the main research areas, and possible directions for future research are also discussed.

Therefore, this paper reviews WECs in low energy seas to fill the current knowledge gap and is divided into six sections. Section 1 introduces the background. Section 2 reviews the body of knowledge on each examined low energy sea along with recent advances. Section 3 provides an overview of the capacity factors (CFs) of different WECs in low energy seas, which is a good indicator of their economically viability, while Section 4 lists the optimum scaling factors. In Section 5 the influence of the local wave regime on WEC performance is discussed, while Section 6 deals with WEC secondary functions, environmental issues, and the effect of climate change on the wave regime of low energy seas. Concluding remarks are given in Section 7.

2. Body of knowledge on low energy seas

2.1. Reviewing methodology

To identify, distil, and critically review the body of knowledge on the five low energy seas under study Scopus, Elsevier's abstract and citation database, was searched in September 2021 for papers, books, and patents. Boolean search was employed using two keywords which were combined with the operator "AND". Specifically, for each examined low energy sea a search string was used which included the term "wave energy converter", which was the first keyword that was fixed, while the second keyword varied and was the name of the sea itself, i.e., i) "Mediterranean"; ii) "Baltic"; iii) "Caspian"; iv) "Black Sea"; and v) "Red Sea", or the word "ocean" to identify the body on knowledge on studies that focued on oceans. In total Scopus identified 144 different bibliographic records, 102 of whom where referring to Mediterranean, 17 to Caspian, 12 to Black Sea, 11 to Baltic Sea, and just 2 to Red Sea (Fig. 1). Furthermore, some relevant works [20–33] that did not include these keywords (primarily the name of one specific country was given instead of the name of the low energy sea) were identified by going through the literature and are included in the analysis. Focus was placed on studies that examined the feasibility of WEC emplacement, performance,

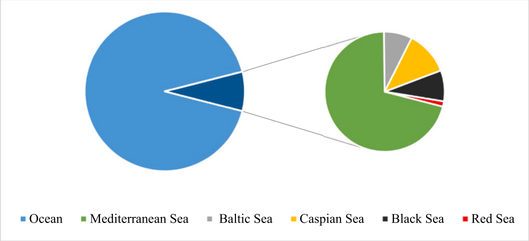

Fig. 1. Studies on WECs focusing on oceans versus on the examined low energy seas.

secondary functions, environmental issues, and the effect of climate change on wave energy, which are considered important aspects for the sustainable introduction of wave energy technology in low energy seas.

2.2. *Studies on oceans versus on low energy seas*

Among the examined low energy seas, the Mediterranean has mainly studied, followed by the Baltic, Caspian, Black, and Red Sea. However, compared to the oceans only a small percentage (8%) of the existing literature has focused on low energy seas (Fig. 1).

Regarding the temporal distribution of the reviewed literature, the Baltic, Caspian, Black, and Red Sea have only recently being studied. However, this is not the case for the Mediterranean Sea where the first study reaches four decades back [34], one more studies was then published in the late 1990s [35] and another in mid 2000s [36], while starting 2008 the publication rate increases (Fig. 2). Most of these studies have focused on the Italian waters, since in contrast to many Mediterranean countries Italy has already in place appropriate schemes to promote R&D on wave energy [37]. In the Caspian Sea the first study on WECs was published in 2009 [38], another in 2013 [39], while starting 2014, the annual publication rate increases, as is the case for the Baltic and the Black Sea (Fig. 2). In the Red Sea only two studies were identified, and these were published only recently [40,41].

The examined WEC types in these areas mainly include point and linear absorbers, whose horizontal dimensions are negligible or comparable to incoming waves, respectively; terminators and attenuators, which can intercept waves or extract energy as waves pass through their length, respectively; and oscillating wave surge converters (OWSCs) and impact structures [42]. Each technology has its own advantages and disadvantages. For example, point absorbers can generate electricity regardless of the wave direction [37,43] while attenuators and terminators should be aligned with the prevailing wave direction [44].

2.3. *Mediterranean Sea*

Various technologies have been proposed for the Mediterranean Sea, ranging from proof of concepts (POCs) to prototype devices to the theoretical installation of larger and more mature WECs.

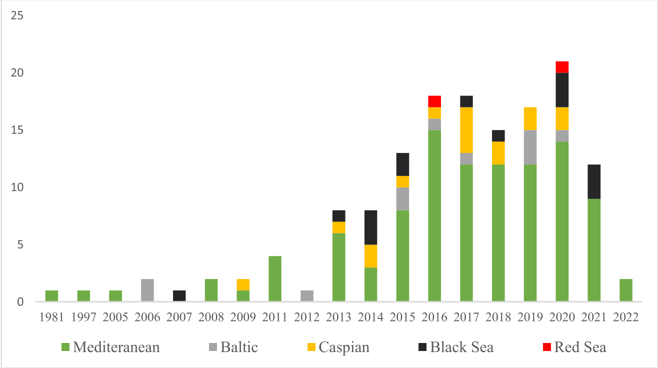

Fig. 2. Published studies on WECs in the examined low energy seas throughout the years.

2.3.1. *Prototype devices*

A large part of the literature in the Mediterranean Sea has focused on POCs and prototype devices, starting as early as 1981 where a patented device (the Melchiorre) that employed the motion of a float to actuate a piston pump was described [34]. However, it will take around 15 years for an another concept to be proposed (Fig. 2), which dealt with a floating buoy equipped with a gyroscopic device [35]. More studies examining POCs and prototype devices appeared in the late 2000s, starting with a tight moored WEC that was theoretically assessed in 2005 using a computed Bretschneider wave spectrum [36]. In 2008, a gyroscopic WEC, able to operate at very low wave heights, typically encountered in the Mediterranean Sea, was proposed [45]. The same year a resonant sea WEC (concrete caisson with a vertical duct equipped with a Wells turbine) was assessed in La Spezia, Italy, where it could absorb more than 30% of the annual incident wave power and also provide protection from wave-induced erosion [46]. In a different study, a 14 years pay-back time was estimated for the Archimedes Waveswing (AWS) WEC when operating in Campania, Italy [47].

In 2011, a prototype palette-type WEC, supported by buoys, was examined in the coast of Turkey (Anamur), suggesting that it could generate electricity in low energy seas [48] wirh a maximum efficiency of 83% [49]. In the same year, the opportunity for testing scaled WECs (SeaBreath) in the Adriatic Sea, Italy and coupling them to other functions to reduce cost, such as integrating them in breakwaters and moored offshore wind farms, was examined [50]. Starting 2013, the publication rate increases (Fig. 2), with studies mainly focusing on prototypes and WECs fit for low power applications, such as the Seaspoon [4,51,52]; Seabreath [53]; standalone spar-buoy oscillating water column (OWC) [54]; optimized OWCs [55–57]; small point absorbers [2]; WaveSAX [58]; ISWEC [22,59–62]; composite sea wall [63]; PMG [64]; DEIM [65–69]; PeWEC [70–72]; PIVOT [73]; PB3 [74]; two-floating buoyage system [43]; or even portable WECs for teaching purposes [75].

2.3.2. *Larger and more mature WEC technologies*

Larger WECs, which have been designed for ocean waves and were even commercially available [42,76–79], have also been examined. Specifically, in 2011 AquaBuOY (250 kW), Pelamis (750 kW), and AWS (2500 kW) were found economically unattractive for the western Italian waters [80]. More works appear in the next few years dealing with the possibility of emplacing large WECs, such as AquaBuOY, Pelamis, and Wave Dragon, in the Italian waters [81]; Pelamis and Wavestar in the Greek Seas [23]; and AquaBuOY, AWS, Langlee, OE buoy, Pelamis, Pontoon, SeaPower, and Wavebob in the Mediterranean Sea [78]. Furthermore, WECs that can be embedded in traditional rubble mound breakwaters, such as the overtopping breakwater for energy conversion (OBREC) [32,82–85]; OWC [56,57,86]; U-shaped oscillating water column (U-OWC), also known as REWEC3 [87–92]; and the Eco Wave Power [84], have been examined. Research has also focused on ISWEC, which started from a 60 kW prototype device [60] and reached technology readiness level 7 [62], while its energy payback and carbon intensity has been estimated at 33 months and 31.46 g CO_2eq kWh^{-1} respectively [93]. More details on deployed WECs in the Mediterranean Sea can be found elsewhere [94,95]. Finally, frameworks for optimizing the geometry, tether angles, and power take-off of point absorber WECs [5,96,97] and the geometry of overtopping WECs [85], and for minimizing the energy cost of heaving WEC layouts [98] have also been proposed.

Overall, it appears that existing technology does not fit the mild Mediterranean wave regime [42,78,81], and therefore currently is not considered a competitive energy resource for wave energy harnessing [99]. Research indicates that existing technology should be downscaled [78] and WECs should be optimized to work within a wave height range of 0.5–4 m [13]. However, for certain technologies and configurations, such as breakwater-integrated OWCs, the milder Mediterranean conditions can be more beneficial for power generation than the north Atlantic's conditions [92], while lower extremes also lead to reduced CAPEX and O&M costs [100].

2.4. Baltic Sea

The Baltic Sea is bounded by Denmark, Estonia, Finland, Latvia, Lithuania, Sweden, Germany, Poland, and Russia and is the largest brackish water sea in the world, having a surface area of more than 393,000 km^2 [6] or 435,000 km^2 [101]. It is a semi-enclosed water body, with more predictable wave energy resource, lower salinity and wave heights, and fewer extreme storms compared to the oceans, suggesting that wave energy harnessing might be economical feasible [8]. As such, several small- or medium-scale WECs, such as single heaving-buoys, pendulum-type, linear tubular devices, SEAREV, Seaspoon, and Eagle WEC, could be promising in the Baltic Sea [9]. However, P_{mean} ranges between 1.5 and 5.2 kW/m [9] and averages at 4 kW/m [8], which for the European and global context is considered relatively low [102].

In 2006, feasible designs of a linear, synchronous, longitudinal-flux permanent-magnet machine (LFM), where a vertical piston is driven by a buoy to produce electricity, were proposed for a calm site in the Baltic Sea [103]. In the same year, a point absorber farm, comprising 379 WECs (10 kW each), was propose for the Baltic Sea, however, many economic and technological barriers were noted for this technology [104]. Six years later, the importance of long-term wave height distributions, for the design and maintenance of resilient WECs, was highlighted [105]. In a different study, three WEC prototypes, based on a linear generator, were installed in the nearshore or in a pier in Lithuania and were found promising for wave energy harnessing in low energy seas, with the one installed on the pier being able to provide electricity for the pier's lighting [6]. Finally, a point absorber WEC developed in the Wave Energy for a Sustainable Archipelago (WESA) project was experimentally examined and it was found that by adjusting the translator's weight to the buoy's volume, power absorption for both upward and downward motions is balanced, thus avoiding the need of retracting springs [106].

Sea ice in the Baltic Sea can greatly affect WEC O&M and survivability and therefore for the development of reliable and cost-effective WECs a good understanding of ice loads is required [107]. Seasonal ice cover can influence wave climate [101], with ice concentration higher than 30% assumed to completely attenuate wave energy [16]. Weather windows and site accessibility, e.g., for installation and O&M, are influenced by the distance from the coast and sea-ice conditions [102]. As such, WECs are not likely to be deployed in areas with high ice concentration over long periods of time [102]. In the context of the WESA project a hexagonal slope shaped torus (HSST) buoy was developed, in order to be able to survive ice interaction while still acting as a point absorber [107].

Furthermore, even though the tidal range in the Baltic Sea is very low (few centimetres to peaks of approximately 24 cm in the Gulf of Finland), during storms wave setups as high as 4 m have been reported, which could affect power production [16]. In this regard, when the Uppsala point absorber L12 WEC was examined under low waves (significant wave height (Hs) = 1 m and energy period (T_e) = 5 s), it was found that the normalized annual energy absorption drastically drops when the mean sea level (MSL) is higher/lower than 0.8 m [16]. More importantly, in the Baltic Sea the onshore wave power exhibits large spatial and seasonal variations and extremely high temporal intermittency, with 30% of the annual wave power arriving within a few days [9]. For example, in the Swedish exclusive economic zone (EEZ) P_{mean} averages at 3.2 kW/m, however, this is achieved by the less frequent high energy storms (up to 12 m extreme wave heights for the 100-years return period), which could have up to four orders of magnitude higher wave power values than the P_{mean} [102].

Therefore, in the Baltic Sea focus should be placed on the low P_{mean} values, seasonal variations and temporal intermittency, wave setup (MSL variations), extreme wave conditions, as well as ice concentration. The latter is a persistent problem that is not encountered in the rest of the examined low energy seas and it should be properly considered for the selection of promising WEC technologies in the Baltic Sea.

2.5. Caspian Sea

The Caspian Sea is the largest, by area, inland body of water in the world (total area 371,000 km^2 [108] or 436,340 km^2 [109]), with 7000 km of coastline that is shared between Azerbaijan, Iran, Kazakhstan, Russia, and Turkmenistan [110]. Research on WEC emplacement began in 2009 (Fig. 2), when it was estimated that 20 parallel-connected 250 kW AWS (covering an area of 4 km^2 in the Iranian offshore) can daily generate up to 15 MW [38]. When different WECs were preliminary screened in the coasts of Mazandaran Province, Iran, Wave Dragon was identified as the most suitable technology [39]. Furthermore, for the wave regime of the Anzali Port, Iran, a bottom-fixed oscillation flap was deemed as a suitable candidate technology [108]. However, another study noted that Wave Dragon, along with Wavestar, and Oyster, were not suitable for emplacement in Anzali, Iran, owning to the low wave power potential [111]. A harmonic pressure WEC was also proposed, where pressure differences between two inlets on the seabed are used to drive a linear induction generator, however, P_{mean} greatly influences its performance [112].

When some of the main WEC technologies, i.e., OWC, attenuator, overtopping, and point absorber, were reviewed in the Caspian Sea setting, the point absorber technology was identified as the most promising, with SEAREV being the most suitable device [10]. The Searaser point absorber has also been numerically assessed and showed potential for industrial applications [113], with the optimum distance between devices being 15 m for the Caspian Sea wave regime [114]. In this regard, to optimise wave energy extraction in offshore areas focus should be placed on the pitch motion of point absorbers [115], while for general cubic shape point absorbers low draft and minimum distance between the centre of gravity and still water level can optimise performance [116]. However, the parallelepipedic hull shape was identified as the geometry that optimises point absorber's power output under the Caspian Sea conditions [110]. The MGR-WEC, which employs a mechanical gear rectifier power take-off system, has also been analytical studied and found highly appropriate for the Caspian Sea low amplitude waves [117].

Overall, among the various examined technologies, point absorbers appear promising for the Caspian Sea, while these should be designed to have a maximum efficiency for waves in the range of 0.5–1 m and periods 4–6 s [118]. This suggest the need for introducing smaller WECs or downscaling existing technology. Finally, if the initial high CAPEX of existing technology is reduced by at least by 30%, then wave energy hybridization with solar and wind energy might be a promising alternative for the Caspian Sea [119].

2.6. Black Sea and Red Sea

In the Black Sea low P_{mean} values have been reported [11,120], with the average being 3 kW/m [8]. Wave heights and lengths usually do not exceed 0.5 m and 15–20 m respectively, while during storms wave heights can reach 6–8 m [121]. However, as was the case with the Mediterranean Sea [14], wave power variability in the Black Sea is low [15], which is beneficial for wave energy harnessing. Furthermore, low P_{mean} values suggest the need for introducing WECs that can be driven by low amplitude waves [122]. In 2007 a WEC that comprised a buoy connected directly to a fixed-bottom linear generator was proposed [15]. A few years later (Fig. 2) the coastal impact of a single Wave Dragon in the marine environment was deemed low, however, it is expected that WEC arrays will have a higher impact [123].

Regarding mature WEC technologies, the expected average electric power of AquabuOY, Pelamis, and Wave Dragon in the Black Sea was estimated at 12, 60, and 391 kW respectively, much lower than the corresponding values in the Atlantic Ocean [124]. The Wavestar, WaveDragon, HeaveBuoy, Sea-wave slot-cone generator (SSG), Sea-based AB, Oyster, and Oyster2 were examined in the Turkish waters and the two first were the most promising devices while the latter the least, suggesting that the correct identification of high energetic geographical locations is essential [125]. Other studies have focused on the effect of both wave climate and water depth in the Black Sea, with the most promising WECs in terms of power output being, from shallow to deep waters, the SSG, WaveDragon, Oyster2, Oceantic and Pontoon [126], while downscaling can greatly improve their performance [127]. WEC design should also be optimized for the local wave regime, since, for example, in terms of energy harnessing heaving point absorbers perform better in the Black Sea when the draft is small compared to the radius [128].

Various concepts for wave energy harnessing were considered in Eregli, Turkey and, since offshore and nearshore systems require additional investment (e.g., for cabling), shoreline converters were deemed more suitable, bearing in mind the possible negative impacts on tourism, social life, and landscape [129]. The positive effect of nearshore wave farms on erosion mitigation was also noted [21], while it was identified that wave WEC-array interactions become more complex as the array size increases, reducing the amount of energy generated by each WEC [130]. A framework to identify promising areas for WEC emplacement, based on wave extremes, intra-annual variations, WEC operational range, and environmental, economic, technical, and social considerations has been also proposed for the Black Sea [131].

Finally, the Red Sea is bounded in the east by Saudi Arabia and Yemen and in the west by Egypt, Sudan, Eritrea, and Djibouti. Wind speeds averages at 10 m/s, both during winter and summer, leading to P_{mean} values of up to 4.5 kW/m in deep waters in central Red Sea but significantly lower near the coastline [12]. Due to the overall low P_{mean} values [12], only two studies were identified. Specifically, the hybridisation of wave energy with wind and solar energy has been proposed in the Red Sea to reduce costs [40], while it has been suggested that fixed-point absorbers could be promising for the Red Sea's low wave power resource [41].

3. WEC capacity factors in low energy seas

WECs have mainly been designed and developed for oceans and therefore they might not be economically viable for low energy seas. A good indicator for assessing WECs economic viability is the load or capacity factor, which is the ratio of the produced electricity at site to the WEC's rated power (nameplate capacity) [124]. Electricity generation at site is typically estimated using the bivariate distribution of Hs and T_e and overlaying them to the WEC's power matrix [132]. For context, in oceans CFs are typically in the range of 30–40% [6], however this is not the case for the examined low energy seas (Table 1).

In the Italian waters, when a high (P_{mean} = 9.5 kW/m) and a low (P_{mean} = 3.9 kW/m) energy spots were examined, CFs were in the range of 1.60–9.4% [80,81]. Similarly, for various nearshore and offshore Italian locations CFs ranged 0.87–8.66% [28], while for eleven WECs in the Italian offshore CFs were typically well below 5%, expect from ISWEC (14–15.5%) and Langlee Robusto (19%) [42] (Table 1). In the French Mediterranean coast CFs greatly varied, depending on the technology and location, ranging from practically zero to as high as 15% (Oceantec) [132]. In Beirut, Lebanon the CFs of Wave Dragon, AquaBuOY, and Pelamis [76] were similar to the ones estimated in the low energy Italian spot [81], while in Menorca, Spain the CFs of these WECs [77] were on par with the ones estimated in the high energy Italian spot [81]. It also appears that Wave Dragon performs better in Spain's wave regime [77], compared to Beirut's [76], and Italy's [81]. This implies the impact of the local wave

Table 1
WEC CFs in the examined low energy seas.

WEC type	Capacity factor (CF) (%)	Location	Reference
10 kW point absorber	~30 (utility factor)	Baltic Sea	[104]
AquaBuOY	3.65–8.39	Italy	[80]
	3.7–8.7	Italy	[81]
	1.33–8.44	Italy	[28]
	~2–2.5*	Italy	[42]
	~5	Lebanon	[76]
	8.2–9.1	Spain	[77]
	6–9	Greece	[133]
	0.44–2.48	Mediterranean/ Black Sea	[134]
	8.4–9.5 (winter)	Black Sea	[124]
	31-33 (downscaled)	Mediterranean	[78]
	6.8 and 26.2 (downscaled)	Turkey	[127]
AWS	1.6–4.5	Italy	[80]
	0.37–4.96	Italy	[28]
	~1–1.2*	Italy	[42]
	2.1–21.1 (downscaled)	Italy	[79]
	0.72–2.77	Mediterranean/ Black Sea	[134]
	24-28 (downscaled)	Mediterranean	[78]
	2.4 and 21.4 (downscaled)	Turkey	[127]
BOF	5–9	Greece	[133]
Ceto	1.38–3.63	Mediterranean/ Black Sea	[134]
F2HB	6–9	Greece	[133]
HeaveBuoy	0.95–4.55	Turkey	[126]
	3.5 and 20.6 (downscaled)	Turkey	[127]
ISWEC	~14–15.5*	Italy	[42]
Langlee	~2–2.1*	Italy	[42]
	12-13 (downscaled)	Mediterranean	[78]
	4.9 and 9.4 (downscaled)	Turkey	[127]
Langlee Robusto	~19.5*	Italy	[42]
Oceantec	~7.5–8*	Italy	[42]
	~0–15*	France	[132]
	3.62–11	Mediterranean/ Black Sea	[134]
	14.4–25	Turkey	[126]
	21.9 and 41.8 (downscaled)	Turkey	[127]
OE Buoy	~2–2.2*	Italy	[42]
	19-21 (downscaled)	Mediterranean	[78]
	4.1 and 17.5 (downscaled)	Turkey	[127]
	1.27–3.63	Mediterranean/ Black Sea	[134]
Oyster	10.99 (upscaled)-19.58	Italy	[79]
	3.44–16.93	Turkey	[126]
	12.5 and 44.1 (downscaled)	Turkey	[127]
Oyster 2	7	Turkey	[126]
	4.2 and 26.3 (downscaled)	Turkey	[127]
Pelamis	4.5–8.46	Italy	[80]
	4.2–9.4	Italy	[81]
	0.87–8.66	Italy	[28]
	~6	Lebanon	[76]
	9.7–10.4	Spain	[77]
	~3–3.5*	Italy	[42]
	~4–11.5 (downscaled) *	Greece	[23]
	8–16	Greece	[133]
	1.41–6.34	Mediterranean/ Black Sea	[134]
	11.9–13.07 (winter)	Black Sea	[124]
	39-42 (downscaled)	Mediterranean	[78]
	7.5 and 33.7 (downscaled)	Turkey	[127]

(*continued on next page*)

Table 1 (*continued*)

WEC type	Capacity factor (CF) (%)	Location	Reference
Pontoon	5.84–14.5	Mediterranean/ Black Sea	[134]
	~2.5–2.7*	Italy	[42]
	15-17 (downscaled)	Mediterranean	[78]
	6.0 and 12.1 (downscaled)	Turkey	[127]
Seabased	~4–4.5*	Italy	[42]
	~0–7.5*	France	[132]
	3.25–10.03	Turkey	[126]
	10 and 23.2 (downscaled)	Turkey	[127]
SeaPower	20-21 (downscaled)	Mediterranean	[78]
SSG	0.89–4.25	Turkey	[126]
	2.9 and 14.9 (downscaled)	Turkey	[127]
Wavebob	~7.5–8*	Italy	[42]
	~0–3*	France	[132]
	1.37–3.51	Mediterranean/ Black Sea	[134]
	32-34 (downscaled)	Mediterranean	[78]
	6.8 and 28.3 (downscaled)	Turkey	[127]
Wave Dragon	3.9–8.8	Italy	[81]
	3.24–7.72	Italy	[28]
	~4	Lebanon	[76]
	10.2–10.8	Spain	[77]
	~2–3*	Italy	[42]
	13.11–44.17 (downscaled)	Italy	[79]
	~0–7.5*	France	[132]
	11–16	Greece	[133]
	1.96–6.77	Mediterranean/ Black Sea	[134]
	8.2–27.8 (winter)	Black Sea	[124]
	6.4 and 38.7 (downscaled)	Turkey	[127]
Wavestar	16.6 (upscaled)-23.65 (600 kW)	Italy	[79]
	~12.5–18 (downscaled)*	Greece	[23]
	13–20	Greece	[133]
	1.26–4.86	Mediterranean/ Black Sea	[134]
	1.31–3.73	Turkey	[126]
	3.8 and 6.6 (downscaled)	Turkey	[127]

~ approximately.
*Values inferred from the corresponding Figure.

regime on different WEC technologies. For promising Greek locations CFs ranged 5%–20% [133], implying that annually up to 1,7 GWh per MW of WEC installed capacity can be produced [37].

When the performances of ten WECs were examined in the Mediterranean and the Black Sea their CFs was in the range 0.44–14.5% (Table 1), with the Black Sea typically yielding lower CFs [134]. During winter, the CFs of AquabuOY, Pelamis, and Wave Dragon in the Black Sea can be as high as 9.5%, 13.07%, and 2.78% [sic] (possibly 27.8%), respectively [124]. However, seasonal fluctuations on the CFs are translated to fluctuations on power generation. When the performance of fifteen WECs was examined in the Turkish waters, CFs greatly varied depending on water depth, with Oyster and Seabased having the highest CFs and Wavestar the lowest [126], while downscaling can greatly improve CFs [127]. Furthermore, in the Baltic Sea the CF of a 10 kW point absorber WEC can be as high as 30% [104], possibly due to its low rated power. Finally, WEC downscaling can substantially improve CFs [23], with values up to 44.17% being reported [79].

Overall, low CFs have been reported for a wide range of different WEC technologies, primarily focusing on the Italian waters (Table 1). Full-sized, let alone upscaled [79], WECs appear not to fit the mild wave regimes of low energy seas. Surprisingly, low rated power WEC technologies, such as Ceto [134] and Seabased [132], did not yielded high CFs, while a 7 MW Wave Dragon performed slightly better than a 1 MW in the Italian waters [42]. The above suggest the need for first identifying the most promising WEC technology for candidate sites and then tailoring (downscaling) it to the local wave regime. This will optimise WEC performance and economic viability.

4. WEC size and downscaling

To maintain profitability, WEC dimensions should not lay far outside the range of the local extreme metocean conditions [102]. Clearly, these are different between oceans and low energy seas. Existing wave energy technology has been designed for ocean waves and therefore WECs tend to be large and bulky to withstand ocean extremes [72]. Nonetheless, during high-energy storms WEC motions are constrained, to ensure survivability [135], and do not generate electricity. Therefore, even though locations with high P_{mean} appear promising, this might not be the case. On the other hand, in low energy seas survivability is not a major issue [37], but existing WECs will fully operate only during the relatively infrequent high-energy storms and waves [1,133] since low energy waves cannot drive them [135]. For example, Wavestar, Oyster, and Wave Dragon underperform in the Caspian Sea [111], while the electricity output of the latter in the Black Sea would be up to an order of magnitude lower than in the Atlantic [124]. In the Mediterranean Sea upscaled versions of Wavestar and Oyster underperform, while the downscaling of Wave Dragon and AWS can greatly improve their CFs [79] (Table 2).

To allow the capture of small waves, typically encountered in the Mediterranean [133], Baltic [9], Caspian [10], Black [122], and Red Sea [41], WEC size reduction, i.e., downscaling, should be considered [78, 81]. This should be carried out by bearing in mind that certain technologies perform better than others in particular wave climates [79], suggesting that each technology should be preferably designed to fit the local wave regime [111]. For example, energy intermittency in heaving point absorbers can be minimised by tailoring their dimensions to the candidate deployment site, e.g., in a case study in Salerno, Italy the optimum buoy diameter was 6 m [136]. For OWCs, when various geometries and wave climates were examined, it was identified that their scaling was site specific, since it strongly depended on the incident wave conditions [137]. Downscaling should also account for constraints associated with the power take-off unit and the device operational profile [2]. An empirical model for identifying OWC optimal design parameters has also been proposed and tested in candidate sites in the Mediterranean Sea [138]. However, to examine the operational range of each WEC technology long-term and high-resolution temporal and spatial wave data are required [13,133].

In the Black Sea different geometries (examined draft to radius ratios: 1, ¾, ½ and ¼) of two types of point absorbers (semi-ellipsoid and semi-elliptical paraboloid buoy) were examined and the semi-ellipsoid buoy with the lower draft to radius ratio (¼) yielded the highest electricity output [130]. On the other hand, when three different sizes (3.7 m, 8.4 m, and 13.7 m) of an axisymmetric point absorber were examined in the Israeli offshore the larger size, which was tuned to less frequent but higher-energy sea-states, performed better in terms of annual power output, particularly when considering its higher survivability [135]. Therefore, smaller devices, per se, do not safeguard optimal operation in terms of electricity generation; particularly when considering that for commercial applications a much higher number of downscaled WECs, compared to full-sized WECs, would be required, which greatly increases the total economic cost of WEC emplacement [42]. However, for low energy seas such as the Mediterranean, smaller devices that are properly spatially distributed to form wave farms could make wave energy exploitation feasible [139].

Table 2
Proposed downscaling ratios for different WECs in the examined low energy seas.

WEC type	Downscaling ratio	Location	Reference
AquaBuOY	0.40	Alghero, Italy	[81]
	0.35	Mazara, Italy	[81]
	0.21*	Tyrrhenian Sea, Italy	[42]
	0.20*	Ionian Sea, Italy	[42]
	0.30	Tobruk, Libya	[78]
	0.30	Crete, Greece	[78]
	0.2	Limanköy, Turkey	[127]
	0.25	Cyprus	[78]
AWS	0.13*	Tyrrhenian Sea, Italy	[42]
	0.11*	Ionian Sea, Italy	[42]
	0.28	Tobruk, Libya	[78]
	0.27	Misurata, Libya	[78]
	0.2	Limanköy, Turkey	[127]
	0.24	Oran, Algeria	[78]
Heave Buoy	0.2	Limanköy, Turkey	[127]
ISWEC	0.26*	Tyrrhenian Sea, Italy	[42]
	0.15*	Ionian Sea, Italy	[42]
	0.5	Ravenna, Italy	[61]
Langlee	0.22*	Tyrrhenian Sea, Italy	[42]
	0.16*	Ionian Sea, Italy	[42]
	0.13	Crete, Greece	[78]
	0.13	Bodrum, Turkey	[78]
	0.4	Limanköy, Turkey	[127]
	0.12	Marseille, France	[78]
Langlee Robusto	0.37*	Tyrrhenian Sea, Italy	[42]
	0.31*	Ionian Sea, Italy	[42]
Oceantec	0.38*	Tyrrhenian Sea, Italy	[42]
	0.4	Limanköy, Turkey	[127]
	0.26*	Ionian Sea, Italy	[42]
OE Buoy	0.26*	Tyrrhenian Sea, Italy	[42]
	0.15*	Ionian Sea, Italy	[42]
	0.21	Almeria, Spain	[78]
	0.20	Nador, Morocco	[78]
	0.2	Limanköy, Turkey	[127]
	0.19	Oran, Algeria	[78]
Oyster	0.2	Limanköy, Turkey	[127]
Oyster 2	0.2	Limanköy, Turkey	[127]
Pelamis	0.40	Alghero, Italy	[81]
	0.30	Mazara, Italy	[81]
	0.3*	Tyrrhenian Sea, Italy	[42]
	0.15*	Ionian Sea, Italy	[42]
	0.42	Rhodes, Greece	[78]
	0.39	Marseille, France	[78]
	0.2	Limanköy, Turkey	[127]
	0.39	Almeria, Spain	[78]
Pontoon	0.22*	Tyrrhenian Sea, Italy	[42]
	0.18*	Ionian Sea, Italy	[42]
	0.17	Crete, Greece	[78]
	0.17	Bodrum, Turkey	[78]
	0.4	Limanköy, Turkey	[127]
	0.15	Perpignan, France	[78]
Seabased	0.27*	Tyrrhenian Sea, Italy	[42]
	0.2	Limanköy, Turkey	[127]
	0.22*	Ionian Sea, Italy	[42]
SeaPower	0.21	Nador, Morocco	[78]
	0.20	Aegadian Islands, Italy	[78]
	0.20	Lampedusa, Italy	[78]
SSG	0.2	Limanköy, Turkey	[127]
Wavebob	0.26*	Tyrrhenian Sea, Italy	[42]
	0.15*	Ionian Sea, Italy	[42]
	0.34	Crete, Greece	[78]
	0.32	Rhodes, Greece	[78]
	0.2	Limanköy, Turkey	[127]
	0.32	Tobruk, Libya	[78]
Wave Dragon	0.40	Alghero, Italy	[81]
	0.30	Mazara, Italy	[81]
	0.2 (7 MW)*	Tyrrhenian Sea, Italy	[42]
	0.32 (7 MW)*	Tyrrhenian Sea, Italy	[42]
	0.16 (7 MW)*	Ionian Sea, Italy	[42]
	0.2	Limanköy, Turkey	[127]
	0.26 (7 MW)*	Ionian Sea, Italy	[42]
Wavestar	0.4	Limanköy, Turkey	[127]

*Values inferred from the corresponding Figure.

Most studies on downscaling have focused on the Mediterranean Sea and primarily in the Italian waters (Table 2). In 2011, one of the first works on WEC downscaling in the Italian waters suggested that AquaBuOY, Pelamis, and AWS are oversized and should be downscaled to become economically attractive [80]. Using the Froude similarity (or similitude) downscaling ratios in the range 0.30–0.40 were proposed for these WECS to reduce intermittency and enhance (by up to 21%) their CFs[81]. In another study in the Italian offshore thirteen WECs (Table 2) were examined and downscaling ratios in the range 0.15–0.35 were proposed [42]. ISWEC was also rescaled (0.5 downscaling ratio), using the Froude similarity, to fit the Adriatic Sea's (Italy) conditions, which exhibits high Hs in extreme storm conditions but low annual P_{mean} [61]. When eight WECs (Table 2) were examined in ten sites in the Mediterranean Sea, the scaling ratio that gave the highest CFs was, by and large, the 0.25, followed by the 0.3 [78]. In the Black Sea the downscaling of fifteen WECs was examined (Table 2) and scaling factors were greatly dependent not only on the location but also on water depth (e.g., for Oceantec the optimum downscaling ratio at 25 m depth was 0.4, at both 50 and 75 m depth 0.5, and at 100 depth 0.6) [127]. Finally, similitude analysis has also been used for upscaling, from laboratory scale, an OWC to fit the moderate Mediterranean climate [57].

Overall, the current body of knowledge suggest that existing technology should be downscaled and tailored to the wave regime of low energy seas to make their eacement economically viable. Downscaling ratios vary, depending on location and technology, with reported ratios being in the range 0.11–0.50 (Table 2). However, downscaling could lead to devices with low nominal capacities, which for commercial applications would translate to large numbers of WECs per MW of installed capacity and thus affect economic viability. Therefore, to identify feasible and commercially attractive WEC designs more research is required towards the scaling characteristics of existing technology.

5. Influence of the local wave regime on WECs

The local wave power resource, along with the annual levels of variation, are critical factors in identifying promising sites for wave energy harnessing [14]. In addition, for the selection of the most promising technology the effect of the local wave regime on each technology (e.g., minimum cut-off and the upper operation threshold) should be known [140]. For example, Pelamis operates best in high-energy waters, while Wavestar functions well both at low- and high-energy waters [9]. This is because the effective operation of each technology largely depends on the ranges of the local wave heights and periods [108]. As such, to identify promising technologies high-resolution spatial and temporal data are required [141]. Seasonal and longer-term variability estimates should be also available, since even though areas with high P_{mean} might appear promising, high temporal variations in the energy availability can render them unattractive for energy extraction [142]. Long-term maximum wave height values are also essential, since WEC design should enable them to withstand severe storm conditions [105].

Apart from wave height, the sensitivity of WECs to the local wave direction should be also known [140,143]. Knowledge of the mean and the extreme wave direction is important, since some technologies, such as attenuators and terminators, are greatly influenced by wave direction [44,123]. In the Mediterranean Sea wave direction variability can be high, even during storms (storm tails vs storm peaks), which should be considered when studying the performance of angle-dependent WECs [144]. Furthermore, in a case study in the Ionian Sea, Greece, a large spreading of mean wave direction was observed, which could lead to uncertainties in terms of real electricity production [145]. In another study in the Italian waters it was highlighted that for point absorber WEC farms both wave direction (layout orientation with the prevailing wave direction) and WEC spacing (optimum distance from 10 to 20 buoy diameters) should be considered to optimise electricity production [29]. In the Caspian Sea the importance of the dominant wave direction on the selection of the most appropriate WEC technology has been highlighted [108].

Regarding the existing body of knowledge on WEC technologies in low energy seas, this has focus both on nearshore and offshore locations. Even though nearshore locations typically offer lower wave energy densities, compared to offshore locations, they provide significant advantages for WEC emplacement, maintenance, and grid connection [63, 101]. In addition, in certain nearshore locations the local bathymetry could create wave energy hotspots [1]. However, to identify promising nearshore locations and assess the performance of different WEC technologies, detailed wave datasets that describe the local wave energy resource should exist.

In low energy seas, the wave power resource has been estimated, by and large, using hindcast (wind forcing generated) data [23,28,42,56, 57,78,79,146,147]. Offshore wave buoy [65], satellite altimetry [148], scatter diagrams for deep water [135], wave atlases [149], and even visual observations [8,105] have being employed as well. However, hindcast data, which are generated by wave models such as the WAve Model (WAM) and Simulating WAves Nearshore (SWAN) model, can be associated with errors, particularly in the nearshore where shoaling and local changes in the bathymetry can grossly influence wave characteristics [1]. For example, SWAN has the tendency to underestimate the Hs and mean wave period [150], while WAM could underestimate the actual wave energy resource [140]. In a case study in a nearshore location in Greece WAM was accurate in approximating P_{mean}, but it overestimated (~23%) the peak maximum wave power potential and underestimated storm duration, while it also had an error of ~19% in estimating the mean direction of incident waves [1]. In the Caspian Sea uncertainties in WEC performance and local wave characteristics can affect, by up to 18% ,the accuracy of the total exploitable wave energy [151].

Therefore, the above suggest the need for wave models calibration, validation, and verification in low energy seas and highlight the importance of long-term actual wave measurements, particularly in nearshore locales where wave models might be associated with errors [1]. This information is vital for selecting the WEC technology and size that better fit the local wave regime.

6. WEC secondary functions, environmental issues, and effect of climate change

The majority of research in the examined low energy seas has focused on power generation, however, other uses or WEC secondary functions have also been examined. These include the use of WECs for desalination [152,153], multi-use offshore platforms [154–156], hydrogen production and storage [155,157], photovoltaic panel integration [65,66,68], pumped-storage hydroelectricity (PSH) [1], and particularly coastal protection [53,87,140] and port integration [7,83, 86,158]. Research has also focused on wave-wind energy co-location. Specifically, WEC farms can protect moored offshore wind farms and reduce the wave impact on wind turbine piles located in their lee [50]. Furthermore, WECs can be incorporated into floating or fixed-support wind turbines to reduce power generation fluctuations, wind and wave energy will be harnessed, and cost, e.g., two Wavestar WECs incorporated into one wind turbine monopole in Latakia, Syria would have a 67 months cost recovery period [159]. Their co-location also improves wind power output (10%–15% due to less surge and a greater stability of the wind turbine [160]) and grid stability, since renewable energy penetration increases, particularly in remote areas [119]. Grid connection (14% of the WEC CAPEX [160]), mooring system (7%–25% of the WEC CAPEX [160]), equipment, and personnel required for O&M are shared and thus cost is reduced [147]. However, currently WECs are expensive and typically provide inconsiderable amounts of electricity, compared to offshore wind, in low energy seas such as the Caspian Sea [119]. Therefore, the co-location of wind and wave energy projects would be more advantageous in areas with a good balance of these two resources and a low correlation between them, which will make electricity generation more steady, dependable, and manageable [147].

Finally, WEC emplacement also promotes job creation. Existing estimates suggests that job creation from the wave energy industry is on par with the offshore wind industry (10 jobs per MW of installed capacity), which for a case study in Greece could create up to 1410 new jobs by 2030 [37]. Other estimates put this number at 10 to 12 direct and indirect jobs generated per MW of WEC installed capacity [6], highlighting wave energy's social and economic perspectives.

6.1. *Coastal protection*

Apart from providing renewable energy, WEC farms can also play an important role in protecting the coasts of low energy seas, such as the Mediterranean [161], the Baltic [9], and the Black Sea [122]. Specifically, WECs greatly reduce incoming wave energy thus limiting, in principle, coastal erosion [1] with a low environmental impact [46]. In 2008 the use of WECs for power generation and erosion mitigation was suggested in the Mediterranean Sea, by incorporating a Wells turbine into a submerged breakwater [46]. A few years later it was suggested that WECs could be used as floating breakwaters for wave sheltering, thus their emplacement could reach economic viability [50]. Not only this, but WECs such as Seabreath can protect the coast and mitigate beach erosion with a lower impact, compared to groynes and offshore breakwaters [53]. Composite seawall WECs, used for both coastal protection and power generation, could also be suitable in low energy seas with a low tidal range [63].

In addition, many coastal areas in the Black Sea suffer from erosion and wave energy extraction from nearshore farms can address, at least partly, this problem [21]. In the lee of wave farms the wave climate and the nearshore water circulation patterns are calmer, hence with proper emplacement WEC farms can be used for coastal protection [134]. In the Baltic Sea it was estimated that a row of point absorber WECs could absorb 26% of the incoming energy over its width, which translated to a 14% attenuation of the incident wave height [104]. Similar result were observed for a DEXA WEC farm in the Mediterranean offshore, where single lines of these devices could only lead to a modest reduction of the incident wave energy, while adding more lines greatly improves coastal protection, with the 8-line configuration being optimal [161].

Simulations of a six Wave Dragons wave farm in western Black Sea (near the Romanian coasts) revelead a strong influnce on the wave characteristics, but only near the farm, with longshore current velocities being strongly affected, but not Hs [123]. Specifically, when emplaced at the nearshore WEC farms have a significant influence in their lee, but this is grossly attenuated at the coastline [162]. Therefore, the closer the WEC farm to the coastline the higher the degree of protection they offer, which suggest that wave farms in the nearshore could be more promising than offshore installations for coastal protection [1]. Furthermore, in a case study in the Spanish Mediterranean waters the importance of the alongshore position of WEC farms was also highlighted, with respect to erosion mitigation [31]. In the same waters the effect of WEC farms in gravel dominated beaches was found beneficial, since erosion was reduced by as much as 44.5%, by limiting Hs and wave run-up [163]. Nonetheless, if WECs are not adequately positioned beach response may shift from accretionary to erosive [31], suggesting the importance of proper emplacement.

Overall, chains or arrays of WECs can play an important role in the protection of locations prone to erosion against high waves [9]. It also appears that WEC farms can encounter the cause and not the effect of erosion, as most of the other engineering solutions considered for coastal protection do [21]. Nonetheless, more research is required, since the magnitude of erosion mitigation depends on many parameters, including WEC type, length, orientation, spacing, and distance from the shore [3], while without proper emplacement they can even accelerate erosion [31].

6.2. Port integration

Ports and harbours are power-hungry during operation, and this is expected to increase due to shore power, i.e., supplying shoreside electricity to ships and boats to keep engines shut during berth [83]. As such, the use of marine energy to provide green energy, and specifically of WEC integration in existing or new port breakwaters [7,83,158] or even piers [6], has recently attracted attention. By doing so, the cost of hybrid WEC-breakwater structures reduces, mainly due cost sharing during construction, installation, and O&M [160]. The reliability of such devices is also improved since these are designed to have a similar behaviour to traditional coastal structures [24]. The generated electricity could be used for port lighting [6] or other uses such as to power harbour lighthouses [20]. Two different technologies, namely the OverTopping Device (OTD) and the OWC, have been considered appropriate for integration in port breakwaters in low energy seas [24].

In 2012 the design stage of an U-OWC incorporated into a vertical breakwater, for harbour protection and wave energy harnessing, was examined in Civitavecchia port, Italy [87]. It could absorb as much as 57% of the incident wave energy, but Wells turbines grossly reduced the amount that is converted to electricity [89]. The optimal configuration of the U-OWC was also examined as a case study in Alghero, Sardinia, Italy [88]. To improve electricity output, it has been proposed that the spacing between each U-OWC chamber should be twice the chamber transversal width [90]. In September 2017, an U-OWC prototype (20 kW Wells turbine without any optimization [95]) was successfully incorporated into a newly build caisson breakwater (total length 578 m) in Civitavecchia port, Italy [91], with plans to incorporate U–OWCs in an additional 16 new breakwaters, bringing the future installed power in this port to 2.5 MW [95].

A modified OWC, named WaveSAX, was also proposed and laboratory tested (scale 1:20), suggesting that its performance was satisfactory for Civitavecchia harbour, Italy [58]. Furthermore, for integration in the planned extension of the vertical breakwater of Giardini Naxos harbour, Italy OWC was more promising than U-OWC, point absorbers, or overtopping WECs, since it allows ship berthing at the offshore during calm conditions [158]. In this regard, the required modifications for OWC integration in port breakwaters would only increase the breakwater's construction cost by ~4%, however, the cost of the Wells turbines is high leading to a 19-years payback period for OWCs [7]. The importance of modelling the air compressibility when selecting the optimal OWC geometry has also been highlighted [164]. On the other hand, for the Port of Valencia, Spain overtopping devices were more promising than OWCs or wave-activated body devices, since the latter are not suggested for ports with heavy vessel traffic, while OWCs have high acoustic impact for urban seaports [83].

OBREC is an OTD concept where the upper part of a conventional rubble mound breakwater is replaced by a frontal ramp and a reservoir, which are designed to capture the energy of overtopping waves [24]. Electricity is generated when the overtopped water is released back to the sea (low head turbines are used) [26]. OBREC has been numerically modelled under various hydraulic and geometric conditions [32,85] and physically modelled at the Aalborg University, Denmark [25,165]. The empirical relations for the prediction of the overtopping and the released water volume, along with the reflection coefficient and wave loading have been also estimated [25,26]. In 2015 one OBREC module was installed at the port of Naples, Italy (total installed power 2.5 kW) [24, 25] and commence operation in January 2016 [26]. The prototype encompasses two similar geometrical configurations, with the main difference being the crest height of the ramp, and it was installed in the middle of the San Vincenzo breakwater (water depth at the toe 25 m), covering an area of 75 m^2 [27].

It appears that WECs CAPEX could be offset against economic gains from improved erosion mitigation and protection of ports and harbours [3], however, further research is required [84]. The existing body of knowledge suggest that it is feasible to integrate WECs in port infrastructure; nonetheless, WECs high CAPEX makes this possibility commercially unattractive.

6.3. Effect of climate change

Apart from the many plights that climate change inflicts on humanity, it also affects the global wave energy resource. Specifically, it has been estimated that from 1948 to 2008 the global wave power was increasing by 0.47%, based on altimetry-corrected global ocean wave (GOW) reanalysis; while high-resolution hindcast data suggest a 2.3% annual increase for the reference period 1994–2012 [166]. Higher wave power values could be beneficial for wave energy harnessing, however, this might affect wave energy's variability might and coastal erosion [167]. Therefore, even though many WEC technologies are not particularly sensitive to sea level rise [161], their behaviour could be affected by changes in the wave power resource. Specifically, WEC selection and operation can be particularly sensitive to the local wave characteristics and therefore changes in the local wave regime could impact WEC operation [9]. The change in the global wave climate is attributed to upper-ocean warming, due to climate change, which increases surface wind energy and by extension wave heights [166].

In low energy seas ,a case study in Menorca island, Spain suggested that even though wave energy's future directional and spatial distribution will likely not be affected, a reduction in its temporal variability is expected, which could enhance WEC efficiency due to the more regular energy distribution throughout the year [168]. On the other hand, with few specific locations aside, projections for the coast of Morocco (20-year hindcast) imply that the future wave energy resource and its directional distribution will remain relatively stable, but the temporal variability will be affected leading to unevenly distribution of wave energy over time [169]. Furthermore, a statistical trend analysis (39-years hindcast) in southern Italy revealed a positive trend in the highest values of Hs and in all T_e values, thus suggesting an increase in the future wave power resource [167]. When a 35-years hindcast was used to identify inter- and intra-annual variations of the wave energy resource in four sites in Western Italy and the North-African coast, a weak trend of increase in the annual P_{mean} was identified [142]. When several parameters, including seasonal and annual variations, were examined in the Algerian basin (39-years hindcast), it was identified that starting from 1995 the wave energy resource has a tendency to increase, and particularly from 2013 to 2017, in the west and central parts of the Algerian coast and primarily during January and February [150]. Finally, in the Black Sea the wave energy regime appears to be subjected to very dynamic changes during the last decades [122], suggesting that climate change is affecting its wave power resource.

Overall, existing research suggest that the wave energy resource in low energy seas is affected, at least to some extent, by climate change, as is the case in the oceans. However, its effects have not yet being fully identified and quantified and therefore more research is required. WECs are typically not sensitive to sea level rise, while the increase in the wave power resource, which is most likely to take place, can be beneficial for WEC emplacement. Nonetheless, wave extremes will have an impact on the selection, emplacement, and O&M of WECs and will reduce survivability. Finally, changes in wave direction, which are less likely to take place, can greatly influence certain WEC technologies.

6.4. Environmental impacts

Wave energy is renewable and therefore, by nature, it can be considered as environmentally friendly, particularly when compared to fossil fuel-based electricity generation. However, as with all technologies and construction activities, environmental impacts are to be expected, which for the case of wave energy mainly occur during construction and installation (e.g., from drilling or dredging) [170]. Furthermore, WECs could potentially affect marine ecosystems, depending on their size, technology, orientation, and lifespan (e.g., during O&M and decommissioning), however little is known about WECs environmental impacts in low energy seas [171]. Specifically, WECs could be a potential source of cumulative stressors on aquatic ecosystems, primarily due to vibrations and low-frequency long-duration noise [172]. For example, when ISWEC installation and operation in Italy was considered, the noise level, which was strongly influenced by high wave heights, it was leading to the masking of fish choruses for up to a 1000 m from the installation site [172]. Furthermore, OWCs have a high acoustic impact that can even affect human communities [83].

On the other hand, when the possible installation of an array of six Wave Dragons in western Black Sea was examined, it was suggested that the level of underwater noise would be very low and possibly harmless to marine fauna, the impact on the seabed from anchor blocks and cabling modest, and the risk of spillages practically non-existent [123]. Furthermore, WECs could possibly act as artificial reefs, which could be beneficial for the local ecosystem. Albeit, they could also introduce new species that might threat the local ecological balance, while hydraulic fluid leakages are possible [170] but not probable [123]. Coastline dynamics could also be affected, with the impact typically depending on bathymetric features and local environmental matrix [123]. Regarding coastal erosion, if properly emplaced, WECs can protected the coast from wave-induced erosion with a low environment impact [46], however without proper emplacement they can accelerate erosion [31].

Unlike other renewable energy sources which result to land use and land use changes or have high visual impact (e.g., wind turbines), this is not the case for wave energy [173]. Specifically, in low energy seas small floating WECs would have a very low visual impact [6], while larger devices would typically appear from the shore as moored ships [123]. Underwater WECs, such as the fully submerged resonant sea WEC, would appear from the shore as submerged breakwaters [46]. However, it has been also suggested that WECs could have negative impact on landscape, thus affecting tourism and social life [129]. On the other hand, it caould also be possible to use the WEC visual impact to promote tourism, through educational and interpretive displays of the wave energy technology [3].

Summing up, apart from renewable electricity generation WECs could act as an innovative way to protect the coast and mitigate erosion [46], with low environmental [161] and aesthetic impact [123], and possibly act as artificial reefs [170]. Furthermore, compared to mature renewables, the presumed environmental impacts of wave energy installations could possibly be lower [6]. Therefore, the environmental gains of WEC operation could largely outweigh their negative impacts, particularly when considering that wave energy can mitigate intermittency and improve renewable energy penetration on the power grid [3]. However, WECs can also be a potential source of cumulative stressors on aquatic ecosystems [172] or, if not properly positioned, they can even lead to beach erosion [31]. Nonetheless, the environmental footprint of wave energy remain grossly unknown [123] and hence more research is required to identify and communicate both the environmental impacts and gains.

6.5. Literature gaps and future research directions

Only a few studies have focused on the economic viability of WECs in low energy seas, with existing technology deemed uneconomical, as was highlighted in a case study in the Ionian Sea, Greece [174]. The underlying reason is traced back to the low CFs, which translate to low electricity outputs [1]. To address this problem, WEC downscaling has been proposed, mainly focusing in the Mediterranean Sea [42,78,81]. Downscaled nominal capacities vary from one to two orders of magnitude lower than the original WECs [78], while constrains from the WEC power take-off unit and its operational profile should be also considered [2]. The above highlight the need for further research on feasible and commercially attractive WEC designs for low energy seas.

Secondary WEC functions, beyond electricity generation, can also make wave energy commercially attractive. WEC integration into port breakwaters [7,83,158] or their use for coastal protection [161], particularly when considering that sea level rise could improve WEC effectiveness in coastal protection [175], have emerged as promising secondary functions. Therefore, it is possible to offset WECs CAPEX against economic gains from their secondary functions, however, as some initial results have highlighted that further research is required towards this end [31].

Support infrastructure, such as grid connections and ports/harbours, has to be located nearby to limit cabling, transmission losses, and maintenance costs, implying that wave energy harnessing is likely to take place in the nearshore [1,176]. To identifying promising nearshore locales and the most appropriate WEC technology accurate knowledge of the nearshore wave power level and directional spread, including monthly, seasonal, intra- and inter-annual variabilities [14], is required. However, in low energy seas available estimates have been generated using numerical models and verified for the offshore, but the veracity of corresponding estimates in the nearshore remains grossly unknown. Therefore, actual long-term measurements in the nearshore are required, along with knowledge of the effect of climate change on the local wave regime.

Finally, the body of knowledge has focused on wave energy's techno-economic aspects, while little attention has been paid on its environmental impacts. WEC impact on local ecosystems should be clearly identified, along with their overall environmental sustainability which can be estimated using the life cycle assessment (LCA) methodology. In this regard, a wide range of carbon footprints has been reported for the oceans, e.g., 33.8 [177] to 64 g CO2 eq/kWh [178] for OWSCs, 86 g CO2eq/kWh for OBREC [179], and 43.7 and 104.5 g CO2eq/kWh for attenuators and point absorbers respectively [178], however, little is known for the environmental performance of (downscaled) WECs in low energy seas. To this end, actual life cycle inventory (LCI) data that correspond to WEC designs, scalings, and power outputs that are fit for low energy seas should be collected, while harmonized multi-issue life cycle impact assessment (LCIA) methods, should be preferably used when assessing the environmental performance of WECs in low energy seas.

All the above can help identify economically viable solutions for wave energy harnessing in low energy seas, with focus preferably being placed on the economic assessment of WECs at early development stages [180]. Furthermore, national and broader, such as EU, funding schemes are required to promote R&D on wave energy. For example, wave energy could potentially play an important role in European Commission's strategic long-term vision for climate neutral economy by 2050 [181]. It could also reduce concerns about energy security and supply in remote coastal areas, while WEC emplacement and maintenance activities are also likely to generate a stable stream of jobs locally, thus benefiting social and economic sustainability in economically deprived remote coastal areas in the Mediterranean and in other low energy seas. However, thus far little attention has been paid to this clean and renewable energy source by decision- and policy-makers, and more financial support for innovative wave energy projects, through R&D and investment subsidies, is required for technology to advance and become commercially viable in low energy seas.

7. Conclusions

The existing body of knowledge on wave energy converts (WECs) in five low energy seas, namely the Mediterranean, Baltic, Caspian, Black, and Red Sea, was critically reviewed and discussed. Compared to the oceans, only a small number of studies were identified, mainly focusing on the Mediterranean Sea where the larger fetch lengths, compared to the remaining low energy Seas, result to higher waves and therefore to a more promising wave energy resource. Many proof-of-concept and prototype devices have been proposed, primarily for the Mediterranean Sea. WECs that have already being deployed in oceans were found to underperform, yielding low capacity factors, which suggest that existing technology is unfit for low energy seas. Therefore, research has recently focused on the downscaling of existing technology, primarily using the Froude similitude or similarity, with scaling ratios in the range of 0.11–0.50 being proposed, depending on the technology and location.

Secondary functions, apart from electricity generation, have also been examined. WECs can be incorporated into ports and harbours breakwaters, while if properly emplaced they can also protect the coast with low environmental impact and address, at least partly, the cause of erosion. Other secondary functions include WECs for desalination, multi-use offshore platforms, hydrogen production and storage, photovoltaic panel integration, pumped-storage hydroelectricity, and wave-wind farms co-location.

Even though WECs appear to be associated with low environmental and aesthetic impact, they could also be associated with negative impacts on aquatic ecosystems, e.g., vibrations and low-frequency long-duration noise, but little attention has been paid in this regard. Regarding the effects of climate change in low energy seas, research suggest that wave energy will increase, temporal variability might decreased, and the directional distribution will, most likely, not be affected.

Future research should focus on downscaling existing wave energy technology for low amplitude waves and deploying small or medium scale WECs in low energy seas. The lessons learned from such deployments could help the technology mature and the industry progress to large scale projects, both in low energy seas and the oceans. Secondary functions, such WECs for coastal protection, could also be exploited to reduce the inital high capital expenditure of WECs, through cost sharing, and make the installation of this technology possible and commercially attractive. More research on the effects of climate change on the wave regime of low energy seas is also required. Finally, to further promote this type of clean energy the environmental impacts and gains, particularly from displacing fossil fuel-based electricity, need to be quantified for different WEC technologies and avenues to improve their environmental performance should also be identified.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.rser.2022.112448.

References

[1] Foteinis S, Hancock J, Mazarakis N, Tsoutsos T, Synolakis CE. A comparative analysis of wave power in the nearshore by WAM estimates and in-situ (AWAC) measurements. The case study of Varkiza, Athens, Greece. Energy 2017;138:500–8.
[2] Piscopo V, Benassai G, Morte RD, Scamardella A. Cost-based design and selection of point absorber devices for the Mediterranean Sea. Energies 2018;11.
[3] Foteinis S, Tsoutsos T. Strategies to improve sustainability and offset the initial high capital expenditure of wave energy converters (WECs). Renew Sustain Energy Rev 2017;70:775–85.
[4] Di Fresco L, Traverso A. The Seaspoon innovative wave energy converter. San Diego: OCEANS 2013 MTS/IEEE -; 2013. An Ocean in Common.
[5] Neshat M, Sergiienko NY, Mirjalili S, Majidi Nezhad M, Piras G, Astiaso Garcia D. Multi-mode wave energy converter design optimisation using an improved moth flame optimisation algorithm. Energies 2021;14:3737.
[6] Blažauskas N, Pašilis A, Knolis A. Potential applications for small scale wave energy installations. Renew Sustain Energy Rev 2015;49:297–305.
[7] Naty S, Viviano A, Foti E. Feaseability study of a wec integrated in the port of Giardini Naxos, Italy. In: Proceedings of the coastal engineering conference; 2016.
[8] Kasiulis E, Punys P, Kofoed JP. Assessment of theoretical near-shore wave power potential along the Lithuanian coast of the Baltic Sea. Renew Sustain Energy Rev 2015;41:134–42.
[9] Kovaleva O, Eelsalu M, Soomere T. Hot-spots of large wave energy resources in relatively sheltered sections of the Baltic Sea coast. Renew Sustain Energy Rev 2017;74:424–37.
[10] Alamian R, Shafaghat R, Miri SJ, Yazdanshenas N, Shakeri M. Evaluation of technologies for harvesting wave energy in Caspian Sea. Renew Sustain Energy Rev 2014;32:468–76.
[11] Akpınar A, Jafali H, Rusu E. Temporal variation of the wave energy flux in hotspot areas of the Black Sea. Sustainability 2019;11:562.
[12] Aboobacker VM, Shanas PR, Alsaafani MA, Albarakati AMA. Wave energy resource assessment for Red Sea. Renew Energy 2017;114:46–58.
[13] Lavidas G, Agarwal A, Venugopal V. Availability and accessibility for offshore operations in the mediterranean sea. J Waterw Port, Coast Ocean Eng 2018;144.
[14] Lavidas G, Venugopal V, Agarwal A. Long-term evaluation of the wave climate and energy potential in the Mediterranean Sea. In: Sustainable hydraulics in the era of global change - proceedings of the 4th European congress of the international association of hydroenvironment engineering and research. IAHR; 2016. p. 247–53. 2016.
[15] Szabó L, Oprea C, Viorel IA, Biró KÁ. Novel permanent magnet tubular linear generator for wave energy converters. In: Proceedings of IEEE international electric machines and drives conference. IEMDC; 2007. p. 983–7. 2007.
[16] Castellucci V, Strömstedt E. Sea level variability in the Swedish Exclusive Economic Zone and adjacent seawaters: influence on a point absorbing wave energy converter. Ocean Sci 2019;15:1517–29.
[17] Kristoferson LA, Bokalders V. 24 - wind power. In: Kristoferson LA, Bokalders V, editors. Renewable energy technologies. Pergamon; 1986. p. 272–82.
[18] McVeigh JC. Chapter 9 - wind power. In: McVeigh JC, editor. Sun power. second ed. Oxford: Pergamon; 1983. p. 192–209.
[19] Breeze P. Chapter 11 - wind power. In: Breeze P, editor. Power generation technologies. third ed. Newnes; 2019. p. 251–73.
[20] Foteinis S, Tsoutsos T, Synolakis C. Numerical modelling for coastal structures design and planning. A case study of the Venetian harbour of Chania, Greece. ISSMGE Int J Geoeng Case Hist 2018;4:232–41. https://doi.org/10.4417/IJGCH-04-04-01 (2018). V, Issue 4, p.
[21] Rusu E. Study of the wave energy propagation patterns in the western Black Sea, vol. 8. Switzerland: Applied Sciences; 2018.
[22] Bracco G, Giorcelli E, Mattiazzo G, Tedeschi E, Molinas M. Control strategies for the ISWEC wave energy system. 2011.
[23] O'Connor M, Lewis T, Dalton G. Techno-economic performance of the Pelamis P1 and Wavestar at different ratings and various locations in Europe. Renew Energy 2013;50:889–900.
[24] Di Lauro E, Maza M, Lara JL, Contestabile P, Losada IJ, Vicinanza D. Numerical analysis of a non-conventional breakwater for wave energy conversion. In: Proc 8th SCACR e International Short Conference on Applied Coastal Research; 2017. Santander, Spain.
[25] Pasquale C, Ferrante V, Enrico Di L, Diego V. FULL-SCALE prototype OF an overtopping breakwater for wave energy conversion. Coast Eng Proc 2017;1.
[26] Contestabile P, Iuppa C, Di Lauro E, Cavallaro L, Andersen TL, Vicinanza D. Wave loadings acting on innovative rubble mound breakwater for overtopping wave energy conversion. Coast Eng 2017;122:60–74.
[27] Contestabile P, Ferrante V, Di Lauro E, Vicinanza D. Prototype overtopping breakwater for wave energy conversion at port of Naples. In: The 26th international ocean and polar engineering conference; 2016. p. 26. June-2 July. Rhodes, Greece.
[28] Vannucchi VC L. Wave energy assessment and performance estimation of state of the art wave energy converters in Italian hotspots. Sustainability 2016;8:1300.
[29] Bozzi S, Giassi M, Moreno Miquel A, Antonini A, Bizzozero F, Gruosso G, et al. Wave energy farm design in real wave climates: the Italian offshore. Energy 2017;122:378–89.
[30] Rodriguez-Delgado C, Bergillos RJ, Iglesias G. Dual wave farms and coastline dynamics: the role of inter-device spacing. Sci Total Environ 2019;646:1241–52.
[31] Rodriguez-Delgado C, Bergillos RJ, Ortega-Sánchez M, Iglesias G. Wave farm effects on the coast: the alongshore position. Sci Total Environ 2018;640–641:1176–86.
[32] Di Lauro E, Lara JL, Maza M, Losada IJ, Contestabile P, Vicinanza D. Stability analysis of a non-conventional breakwater for wave energy conversion. Coast Eng 2019;145:36–52.
[33] Barbariol F, Benetazzo A, Carniel S, Sclavo M. Improving the assessment of wave energy resources by means of coupled wave-ocean numerical modeling. Renew Energy 2013;60:462–71.
[34] Wave energy exploitation using the 'Melchiorre' patented modular energy converter. 1981.
[35] Martellucci L. Evaluation of a sea wave energy converter with variable trim. In: Proceedings of the intersociety energy conversion engineering conference; 1997. p. 1990–5.
[36] Mavrakos SA, Katsaounis GM. Parametric evaluation of the performance characteristics of tight moored wave energy converters. In: Proceedings of the international conference on offshore mechanics and arctic engineering - OMAE; 2005. p. 751–7.
[37] Lavidas G. Energy and socio-economic benefits from the development of wave energy in Greece. Renew Energy 2019;132:1290–300.
[38] Faiz J, Ebrahimi-Salari M. Design and simulation of a 250 kW linear permanent magnet generator for wave energy to electric energy conversion in Caspian Sea. In: 1st international conference on sustainable power generation and supply. SUPERGEN '09; 2009.
[39] Fadaee Nejad M, Shariati O, Mohd Zin AAB. Feasibility study of wave energy potential in southern coasts of Caspian Sea in Iran. In: Proceedings of the 2013

IEEE 7th international power engineering and optimization conference. PEOCO; 2013. p. 57–60. 2013.

[40] Langodan S, Viswanadhapalli Y, Dasari HP, Knio O, Hoteit I. A high-resolution assessment of wind and wave energy potentials in the Red Sea. Appl Energy 2016; 181:244–55.

[41] Alkhayyat M, Brahimi T, Langodan S, Hoteit I. Wave energy converters: barriers and drivers. In: Proceedings of the international conference on industrial engineering and operations management; 2020. p. 2860–71. March ed.

[42] Aristodemo F, Algieri Ferraro D. Feasibility of WEC installations for domestic and public electrical supplies: a case study off the Calabrian coast. Renew Energy 2018;121:261–85.

[43] Curto D, Viola A, Franzitta V, Trapanese M, Cardona F. A new solution for sea wave energy harvesting, the proposal of an ironless linear generator. J Mar Sci Eng 2020;8.

[44] Karathanasi F, Soukissian T, Belibassakis K. Directional extreme value models in wave energy applications. Atmosphere 2020;11:1–26.

[45] Bracco G, Giorcelli E, Mattiazzo G. One degree of freedom gyroscopic mechanism for wave energy converters. In: Proceedings of the ASME design engineering technical conference. PARTS A AND B ed; 2008. p. 895–902.

[46] Filianoti P, Camporeale SM. A linearized model for estimating the performance of submerged resonant wave energy converters. Renew Energy 2008;33:631–41.

[47] Benassai G, Dattero M, Maffucci A. Wave energy conversion systems: optimal localization procedure. WIT Trans Ecol Environ 2009;126:129–38.

[48] Buldu G, Canbolat H, Tutar M. The design of a palette-type wave energy converter system supported by Buoys. In: 2011 10th international conference on environment and electrical engineering, EEEICEU 2011 - conference proceedings; 2011.

[49] Buldu G, Canbolat H, Tutar M, Ali MB. A study analysis for a self excited induction generator for a sea wave energy extraction application. In: Proceeding of the international conference on electrical power quality and utilisation. EPQU; 2011. p. 722–7.

[50] Martinelli L. Wave Energy Converters under mild wave climates. OCEANS'11 - MTS/IEEE Kona, Program Book. 2011.

[51] Di Fresco L, Traverso A. Energy conversion of orbital motions in gravitational waves: simulation and test of the Seaspoon wave energy converter. Energy Convers Manag 2014;86:1164–72.

[52] Barberis S, Roncallo F, Traverso A. Towards innovative district energy management: a case study with stochastic renewable generators. Entrep Sustain Iss 2017;4:294–309.

[53] Martinelli L, Pezzutto P, Ruol P. Experimentally based model to size the geometry of a new OWC device, with reference to the mediterranean sea wave environment. Energies 2013;6:4696–720.

[54] Oikonomou CLG, Gomes RPF, Gato LMC. Unveiling the potential of using a spar-buoy oscillating-water-column wave energy converter for low-power stand-alone applications. Appl Energy 2021;292:116835.

[55] Simonetti I, Crema I, Cappietti L, El Safti H, Oumeraci H. Site-specific optimization of an OWC wave energy converter in a Mediterranean area. In: Progress in renewable energies offshore - proceedings of 2nd international conference on renewable energies offshore. RENEW; 2016. p. 343–50. 2016.

[56] Ciappi L, Cheli L, Simonetti I, Bianchini A, Talluri L, Cappietti L, et al. Wave-to-wire models of wells and impulse turbines for oscillating water column wave energy converters operating in the Mediterranean Sea. Energy 2022:238.

[57] Ciappi L, Cheli L, Simonetti I, Bianchini A, Manfrida G, Cappietti L. Wave-to-wire model of an oscillating-water-column wave energy converter and its application to mediterranean energy hot-spots. Energies 2020;13.

[58] Agate G, Amicarelli A, Danelli A, Peviani M. Optimization of the wavesax device: numerical modelling and ocean wave basin tests. MARINE 2015 - Comput Method Mar Eng VI 2015:119–27.

[59] Bracco G, Casassa M, Giorcelli E, Giorgi G, Mattiazzo G, Passione B, et al. Application of sub-optimal control techniques to a gyroscopic wave energy converter. In: Renewable energies offshore - 1st international conference on renewable energies offshore. RENEW; 2015. p. 265–9. 2014.

[60] Cagninei A, Raffero M, Bracco G, Giorcelli E, Mattiazzo G, Poggi D. Productivity analysis of the full scale inertial sea wave energy converter prototype: a test case in Pantelleria Island. J Renew Sustain Energy 2015;7.

[61] Alessi A, Boi E, Malkowski A, Carlo C, Cresci B, Zanon F, et al. Towards wave energy utilization for oil and gas assets and wave farms development: the adriatic sea demonstration case. In: Offshore mediterranean conference and exhibition 2019. OMC; 2019. 2019.

[62] Mattiazzo G. State of the art and perspectives of wave energy in the Mediterranean Sea: backstage of ISWEC. Front Energy Res 2019;7.

[63] Buccino M, Stagonas D, Vicinanza D. Development of a composite sea wall wave energy converter system. Renew Energy 2015;81:509–22.

[64] Viola A, Franzitta V, Curto D, Trapanese M, Di Dio V, Cipriani G, et al. Design of wave energy converter (WEC): a prototype installed in Sicily. In: MTS/IEEE oceans 2015 - Genova. Discovering Sustainable Ocean Energy for a New World; 2015.

[65] Franzitta VC D, Rao D. Energetic sustainability using renewable energies in the Mediterranean Sea. Sustainability 2016;8:1164.

[66] Franzitta V, Curto D, Milone D, Rao D. Assessment of renewable sources for the energy consumption in Malta in the Mediterranean Sea. Energies 2016;9.

[67] Viola A, Curto D. Numerical simulation of wave energy production through experimental tool. In: Conference proceedings - 2017 17th IEEE international conference on environment and electrical engineering and 2017 1st IEEE industrial and commercial power systems Europe. EEEIC/I and CPS Europe; 2017. 2017.

[68] Viola A, Trapanese M. An innovative wave energy converter in the Mediterranean Sea. 2018 OCEANS - MTS/IEEE Kobe Techno-Oceans, OCEANS - Kobe; 2018. 2018.

[69] Curto D, Favuzza S, Franzitta V, Musca R, Navarro Navia MA, Zizzo G. Evaluation of the optimal renewable electricity mix for Lampedusa island: the adoption of a technical and economical methodology. J Clean Prod 2020:263.

[70] Nicola P, Giovanni B, Biagio P, Antonello SS, Giacomo V, Giuliana M, et al. Wave tank testing of a pendulum wave energy converter 1:12 scale model. Int J Appl Mech 2017;9:1750024.

[71] Pozzi N, Bonetto A, Bonfanti M, Bracco G, Dafnakis P, Giorcelli E, et al. PeWEC: preliminary design of a full-scale plant for the mediterranean sea. In: NAV international conference on ship and shipping research; 2018. p. 504–14. 221499 ed.

[72] Pozzi N, Bracco G, Passione B, Sirigu SA, Mattiazzo G. PeWEC: experimental validation of wave to PTO numerical model. Ocean Eng 2018;167:114–29.

[73] Coiro DP, Troise G, Bizzarrini N. Experiences in developing tidal current and wave energy devices for Mediterranean Sea. Front Energy Res 2018;6.

[74] Alessi A, Boi E, Malkowski A, Cesari C, Cresci B, Zanon F, et al. Application of wave energy converter technology to subsea power requirements and asset integrity in oil and gas field developments. In: Offshore mediterranean conference and exhibition. OMC; 2019. 20192019.

[75] Liermann M, Samhoury O, Atshan S. Energy efficiency of pneumatic power take-off for wave energy converter. Int J Mar Energy 2016;13:62–79.

[76] Aoun NS, Harajli HA, Queffeulou P. Preliminary appraisal of wave power prospects in Lebanon. Renew Energy 2013;53:165–73.

[77] Sierra JP, Mösso C, González-Marco D. Wave energy resource assessment in Menorca (Spain). Renew Energy 2014;71:51–60.

[78] Bozzi S, Besio G, Passoni G. Wave power technologies for the Mediterranean offshore: scaling and performance analysis. Coast Eng 2018;136:130–46.

[79] Majidi Nezhad M, Groppi D, Rosa F, Piras G, Cumo F, Garcia DA. Nearshore wave energy converters comparison and Mediterranean small island grid integration. Sustain Energy Technol Assessments 2018;30:68–76.

[80] Archetti R, Bozzi S, Passoni G. Feasibility study of a wave energy farm in the western Mediterranean Sea: comparison among different technologies. In: Proceedings of the international conference on offshore mechanics and arctic engineering - OMAE; 2011. p. 447–52.

[81] Bozzi S, Archetti R, Passoni G. Wave electricity production in Italian offshore: a preliminary investigation. Renew Energy 2014;62:407–16.

[82] Iuppa C, Contestabile P, Cavallaro L, Foti E, Vicinanza D. Hydraulic performance of an innovative breakwater for overtopping wave energy conversion. Sustainability 2016;8.

[83] Cascajo R, García E, Quiles E, Correcher A, Morant F. Integration of marine wave energy converters into seaports: a case study in the port of Valencia. Energies 2019;12.

[84] Cascajo R, García E, Quiles E, Morant F, Correcher A. Wave energy assessment at Valencia Gulf and comparison of energy production of most suitable wave energy converters. Int J Environ Res Publ Health 2020;17:8473.

[85] Cavallaro L, Iuppa C, Castiglione F, Musumeci RE, Foti E. A simple model to assess the performance of an overtopping wave energy converter embedded in a port breakwater. J Mar Sci Eng 2020;8:858.

[86] Lavidas G, De Leo F, Besio G. Blue growth development in the Mediterranean Sea: quantifying the benefits of an integrated wave energy converter at Genoa harbour. Energies 2020;13:4201.

[87] Arena F, Romolo A, Malara G, Ascanelli A. On design and building of a U-OWC wave energy converter in the mediterranean sea: a case study. In: Proceedings of the international conference on offshore mechanics and arctic engineering - OMAE; 2013.

[88] Arena F, Laface V, Malara G, Strati FM. Optimal configuration of a U-OWC wave energy converter. In: Renewable energies offshore - 1st international conference on renewable energies offshore. RENEW; 2015. p. 429–36. 2014.

[89] Arena F, Malara G, Romolo A. A U-OWC wave energy converter in the Mediterranean sea: preliminary results on the monitoring system of the first prototype. In: Renewable energies offshore - 1st international conference on renewable energies offshore. RENEW; 2015. p. 417–21. 2014.

[90] Malara G, Arena F. Response of U-Oscillating Water Column arrays: semi-analytical approach and numerical results. Renew Energy 2019;138:1152–65.

[91] Romolo A, Henriques J, Gato LMC, Malara G, Laface V, Gomes RPF, et al. Power take-off selection for a u-shaped owc wave energy converter. In: Proceedings of the international conference on offshore mechanics and arctic engineering - OMAE; 2019.

[92] Fox BN, Gomes RPF, Gato LMC. Analysis of oscillating-water-column wave energy converter configurations for integration into caisson breakwaters. Appl Energy 2021;295:117023.

[93] Di Muro A, Sirigu SA, Giorgi G, Gerboni R, Bracco G, Carpignano A, et al. Life cycle assessment for the ISWEC wave energy device. Cham: Springer International Publishing; 2021. p. 515–23.

[94] Dialyna E, Tsoutsos T. Wave energy in the mediterranean sea: resource assessment, deployed wecs and prospects. Energies 2021:14.

[95] IEA-OES. Annual report: an overview of ocean energy activities in 2020. 2020. p. 188.

[96] Neshat M, Sergiienko NY, Amini E, Majidi Nezhad M, Astiaso Garcia D, Alexander B, et al. A new Bi-level optimisation framework for optimising a multi-mode wave energy converter design: a case study for the marettimo island, Mediterranean Sea. Energies 2020;13:5498.

[97] Barbarelli S, Amelio M, Castiglione T, Florio G, Scornaienchi NM. Design and analysis of a new wave energy converter based on a point absorber and a

hydraulic system harvesting energy from waves near the shore in calm seas. Int J Energy Res 2021;45:661–90.

[98] Loukogeorgaki E, Michailides C, Lavidas G, Chatjigeorgiou IK. Layout optimization of heaving Wave Energy Converters linear arrays in front of a vertical wall. Renew Energy 2021;179:189–203.

[99] Friedrich D, Lavidas G. Evaluation of the effect of flexible demand and wave energy converters on the design of hybrid energy systems. IET Renew Power Gener 2017;11:1113–9.

[100] Lavidas G, Venugopal V. Wave energy resource evaluation and characterisation for the Libyan Sea. Int J Mar Energy 2017;18:1–14.

[101] Nilsson E, Rutgersson A, Dingwell A, Björkqvist JV, Pettersson H, Axell L, et al. Characterization of wave energy potential for the Baltic Sea with focus on the Swedish exclusive economic zone. Energies 2019;12.

[102] Nilsson E, Wrang L, Rutgersson A, Dingwell A, Strömstedt E. Assessment of extreme and metocean conditions in the Swedish exclusive economic zone for wave energy. Atmosphere 2020:11.

[103] Wolfbrandt A. Automated design of a linear generator for wave energy converters - a simplified model. IEEE Trans Magn 2006;42:1812–9.

[104] Bernhoff H, Sjöstedt E, Leijon M. Wave energy resources in sheltered sea areas: a case study of the Baltic Sea. Renew Energy 2006;31:2164–70.

[105] Kasiulis E. Probability distributions of wave heights in the Lithuanian coast. Research for Rural Development. 2012. p. 152–8.

[106] Lejerskog E, Strömstedt E, Savin A, Boström C, Leijon M. Study of the operation characteristics of a point absorbing direct driven permanent magnet linear generator deployed in the Baltic Sea. IET Renew Power Gener 2016;10:1204–10.

[107] Savin A, Strömstedt E, Leijon M. Full-scale measurement of reaction force caused by level ice interaction on a buoy connected to a wave energy converter. J Cold Reg Eng 2019;33.

[108] Hadadpour S, Etemad-Shahidi A, Jabbari E, Kamranzad B. Wave energy and hot spots in Anzali port. Energy 2014;74:529–36.

[109] Alamian R, Shafaghat R, Ramzan-Nejad M, Miri SJ. Numerical simulation of nonlinear waves in numerical wave tank using boundary element method. In: Progress in clean energy, vol. 1. Analysis and Modeling; 2015. p. 857–68.

[110] Alamian R, Shafaghat R, Safaei MR. Multi-objective optimization of a pitch point absorber wave energy converter. Switzerland): Water; 2019. p. 11.

[111] Nezhad MM, Groppi D, Piras G. Nearshore wave energy assessment of Iranian coastlines. In: Proceedings of the world congress on new technologies; 2018.

[112] Jahangir MH, Khatibi A. Site selection of harmonic pressure water energy convertor systems on the south coast of the Caspian Sea using cluster analysis. Sustain Energy Technol Assessments 2020;38:100678.

[113] Babajani A, Jafari M, Hafezisefat P, Mirhosseini M, Rezania A, Rosendahl L. Parametric study of a wave energy converter (Searaser) for Caspian Sea. Energy Procedia; 2018. p. 334–42.

[114] Babajani AA, Jafari M, Hafezi Sefat P. Numerical investigation of distance effect between two Searasers for hydrodynamic performance. Alex Eng J 2016;55:2257–68.

[115] Alamian R, Shafaghat R, Shadloo MS, Bayani R, Amouei AH. An empirical evaluation of the sea depth effects for various wave characteristics on the performance of a point absorber wave energy converter. Ocean Eng 2017;137:13–21.

[116] Alamian R, Shafaghat R, Bayani R, Amouei AH. An experimental evaluation of the effects of sea depth, wave energy converter's draft and position of centre of gravity on the performance of a point absorber wave energy converter. J Mar Eng Technol 2017;16:70–83.

[117] Pendar MR, Sarjan H. Design, fabrication, and testing of a shore-line wave energy converter with mechanical gear motion rectifier. In: Icee 2019 - 27th Iranian conference on electrical engineering; 2019. p. 2100–5.

[118] Alamian R, Shafaghat R, Hosseini SS, Zainali A. Wave energy potential along the southern coast of the Caspian Sea. Int J Mar Energy 2017;19:221–34.

[119] Jahangir MH, Shahsavari A, Vaziri Rad MA. Feasibility study of a zero emission PV/Wind turbine/Wave energy converter hybrid system for stand-alone power supply: a case study. J Clean Prod 2020;262:121250.

[120] Rusu L. Assessment of the wave energy in the black sea based on a 15-year hindcast with data assimilation. Energies 2015;8:10370–88.

[121] Bekirov EA, Voskresenskaya SN, Asanov MM, Murtazaev ER. Analysis of the sea waves energy characteristics in the Black Sea region. In: 2020 international multi-conference on industrial engineering and modern technologies (FarEastCon); 2020. p. 1–4.

[122] Rusu L. Wave modelling with data assimilation to evaluate the wave energy patterns in the Black Sea. In: International multidisciplinary scientific GeoConference surveying geology and mining ecology management, vol. 4. SGEM; 2015. p. 597–604. ed.

[123] Diaconu S, Rusu E. The environmental impact of a wave dragon array operating in the Black Sea. Sci World J 2013;2013.

[124] Rusu E. Evaluation of the wave energy conversion efficiency in various coastal environments. Energies 2014;7:4002–18.

[125] Gul Majidi A, Bingölbali B, Akplnar A, Rusu E. Dimensionless normalized wave power in the hot-spot areas of the Black Sea. In: E3S web of conferences; 2020.

[126] Majidi AG, Bingölbali B, Akpınar A, Rusu E. Wave power performance of wave energy converters at high-energy areas of a semi-enclosed sea. Energy 2021;220:119705.

[127] Majidi A, Bingölbali B, Akpınar A, Iglesias G, Jafali H. Downscaling wave energy converters for optimum performance in low-energy seas. Renew Energy 2021;168:705–22.

[128] Erselcan İÖ, Kükner A. A parametric optimization study towards the preliminary design of point absorber type wave energy converters suitable for the Turkish coasts of the Black Sea. Ocean Eng 2020;218:108275.

[129] Keskin Citiroglu H, Okur A. An approach to wave energy converter applications in Eregli on the western Black Sea coast of Turkey. Appl Energy 2014;135:738–47.

[130] Erselcan İÖ, Kükner A. A numerical analysis of several wave energy converter arrays deployed in the Black Sea. Ocean Eng 2017;131:68–79.

[131] Şan M, Akpınar A, Bingölbali B, Kankal M. Geo-spatial multi-criteria evaluation of wave energy exploitation in a semi-enclosed sea. Energy 2021;214:118997.

[132] Onea F, Rusu E. Sensitivity analysis of the wave energy converters operating in the French coastal waters. Int J Smart Grid Clean Energy 2019;8:239–44.

[133] Lavidas G, Venugopal V. A 35 year high-resolution wave atlas for nearshore energy production and economics at the Aegean Sea. Renew Energy 2017;103:401–17.

[134] Rusu L, Onea F. Assessment of the performances of various wave energy converters along the European continental coasts. Energy 2015;82:889–904.

[135] Stuhlmeier R, Xu D. WEC design based on refined mean annual energy production for the Israeli Mediterranean coast. J Waterw Port, Coast Ocean Eng 2018;144:06018002.

[136] Piscopo V, Benassai G, Cozzolino L, Della Morte R, Scamardella A. A new optimization procedure of heaving point absorber hydrodynamic performances. Ocean Eng 2016;116:242–59.

[137] Simonetti I, Cappietti L, Elsafti H, Oumeraci H. Optimization of the geometry and the turbine induced damping for fixed detached and asymmetric OWC devices: a numerical study. Energy 2017;139:1197–209.

[138] Simonetti I, Cappietti L, Oumeraci H. An empirical model as a supporting tool to optimize the main design parameters of a stationary oscillating water column wave energy converter. Appl Energy 2018;231:1205–15.

[139] Miquel AM, Antonini A, Archetti R, Bozzi S, Lamberti A. Non-linear modelling of a heaving point absorber: the surge effect. Int J Mar Energy 2017;19:95–109.

[140] Vicinanza D, Contestabile P, Ferrante V. Wave energy potential in the north-west of Sardinia (Italy). Renew Energy 2013;50:506–21.

[141] Martzikos NT, Soukissian TH. Modelling of the sea surface elevation based on a data analysis in the Greek seas. Appl Ocean Res 2017;69:76–86.

[142] Besio G, Mentaschi L, Mazzino A. Wave energy resource assessment in the Mediterranean Sea on the basis of a 35-year hindcast. Energy 2016;94:50–63.

[143] Soukissian TH, Karathanasi FE. Joint modelling of wave energy flux and wave direction. Processes 2021;9:460.

[144] Laface V, Arena F, Soares CG. Directional analysis of sea storms. Ocean Eng 2015;107:45–53.

[145] Ferraro DA, Aristodemo F, Veltri P. Wave energy resources along calabrian coasts (Italy). In: Proceedings of the coastal engineering conference; 2016.

[146] Franzitta V, Rao D, Curto D, Viola A. Greening island: renewable energies mix to satisfy electrical needs of Pantelleria in Mediterranean sea. OCEANS 2016 MTS/IEEE Monterey; 2016. p. 1–6.

[147] Ferrari F, Besio G, Cassola F, Mazzino A. Optimized wind and wave energy resource assessment and offshore exploitability in the Mediterranean Sea. Energy 2020;190:116447.

[148] Šljivac D, Temiz I, Nakomčić-Smaragdakis B, Žnidarec M. Integration of wave power farms into power systems of the Adriatic islands: technical possibilities and cross-cutting aspects. Water 2021;13:13.

[149] Piscopo V, Scamardella A. Design of a new point absorber with a fully submerged toroidal shape. Ocean Eng 2019;191:106492.

[150] Amarouche K, Akpınar A, Bachari NEI, Houma F. Wave energy resource assessment along the Algerian coast based on 39-year wave hindcast. Renew Energy 2020;153:840–60.

[151] Amirinia G, Kamranzad B, Mafi S. Wind and wave energy potential in southern Caspian Sea using uncertainty analysis. Energy 2017;120:332–45.

[152] Viola A, Franzitta V, Trapanese M, Curto D. Nexus water & energy: a case study of wave energy converters (wecs) to desalination applications in sicily. Int J Heat Technol 2016;34:S379–86.

[153] Hwang JY, Kiung Y. Wave energy converters (WEC) for desalination applications. A potential application in Mediterranean Sea. OCEANS 2017 - Anchorage 2017:1–6.

[154] Zanuttigh B, Angelelli E, Kortenhaus A, Koca K, Krontira Y, Koundouri P. A methodology for multi-criteria design of multi-use offshore platforms for marine renewable energy harvesting. Renew Energy 2016;85:1271–89.

[155] Urbano G, Rocco E. In: Fuelling regional growth: still a dream or a concrete possibility? Offshore mediterranean conference and exhibition. OMC; 2019. 20192019.

[156] Adam F, Dierken P, Aye MM, Wittmann F, Schmitt C, Cobzaru A. Design and engineering of an energy maintenance hub superstructure. Singapore: Springer Singapore; 2022. p. 165–78.

[157] Colucci A, Boscaino V, Cipriani G, Curto D, Di Dio V, Franzitta V, et al. An inertial system for the production of electricity and hydrogen from sea wave energy. In: Oceans 2015. Washington: MTS/IEEE; 2016.

[158] Naty S, Viviano A, Foti E. Wave energy exploitation system integrated in the coastal structure of a mediterranean port. Sustainability 2016;8.

[159] Moghimi M, Derakhshan S, Motawej H. A mathematical model development for assessing the engineering and economic improvement of wave and wind hybrid energy system. Iranian J Sci Technol Trans Mech Eng 2020;44:507–21.

[160] Pantusa D, Francone A, Tomasicchio GR. Floating offshore renewable energy farms. A life-cycle cost analysis at Brindisi, Italy. Energies 2020;13:6150.

[161] Zanuttigh B, Angelelli E. Experimental investigation of floating wave energy converters for coastal protection purpose. Coast Eng 2013;80:148–59.

[162] Rusu E, Diaconu S. Costal impact of a wave dragon based energy farm operating on the near shore of the Black Sea. Indian J Mar Sci 2014;43:163–75.
[163] Bergillos RJ, López-Ruiz A, Medina-López E, Moñino A, Ortega-Sánchez M. The role of wave energy converter farms on coastal protection in eroding deltas, Guadalfeo, southern Spain. J Clean Prod 2018;171:356–67.
[164] Simonetti I, Cappietti L. The impact of modelling air compressibility in the selection of optimal owc design parameters in site specific wave conditions. In: Proceedings of the international conference on offshore mechanics and arctic engineering. OMAE; 2019.
[165] Vicinanza D, Contestabile P, , Quvang Harck Nørgaard J, Lykke Andersen T. Innovative rubble mound breakwaters for overtopping wave energy conversion. Coast Eng 2014;88:154–70.
[166] Reguero BG, Losada IJ, Méndez FJ. A recent increase in global wave power as a consequence of oceanic warming. Nat Commun 2019;10:205.
[167] Caloiero T, Aristodemo F, Algieri Ferraro D. Trend analysis of significant wave height and energy period in southern Italy. Theor Appl Climatol 2019;138: 917–30.
[168] Sierra JP, Casas-Prat M, Campins E. Impact of climate change on wave energy resource: the case of Menorca (Spain). Renew Energy 2017;101:275–85.
[169] Sierra JPC R, Mestres M, Mösso C, Lionello P, Marzo L. Impact of climate change on wave energy resource in the Mediterranean coast of Morocco. Energies 2020; 13:2993.
[170] Aderinto TL H. ocean wave energy converters: status and challenges. Energies 2018;11:1250.
[171] Riefolo L, Lanfredi C, Azzellino A, Vicinanza D. Environmental impact assessment of wave energy converters: a review. In: Proceedings of the international conference on applied coastal research SCACR; 2015. Florence, Italy.
[172] Buscaino G, Mattiazzo G, Sannino G, Papale E, Bracco G, Grammauta R, et al. Acoustic impact of a wave energy converter in Mediterranean shallow waters. Sci Rep 2019;9.
[173] Curto D, Franzitta V, Trapanese M, Cirrincione M. A preliminary energy assessment to improve the energy sustainability in the small islands of the mediterranean sea. J Sustain Dev Energy, Water Environ Syst 2020;8:735–53.
[174] Hutcheson J, De Andrés A, Jeffrey H. Risk vs. Reward: a methodology to assess investment in marine energy. Sustainability 2016;8:873.
[175] Rodriguez-Delgado C, Bergillos RJ, Iglesias G. Dual wave farms for energy production and coastal protection under sea level rise. J Clean Prod 2019;222: 364–72.
[176] Vannucchi V, Cappietti L, Falcão AFO. Estimation of the offshore wave energy potential of the Mediterranean Sea and propagation toward a nearshore area. In: 4th international conference on ocean energy; 2012. Dublin, Ireland.
[177] Apolonia M, Simas T. Life cycle assessment of an oscillating wave surge energy converter. J Mar Sci Eng 2021;9:206.
[178] Uihlein A. Life cycle assessment of ocean energy technologies. Int J Life Cycle Assess 2016;21:1425–37.
[179] Patrizi N, Pulselli RM, Neri E, Niccolucci V, Vicinanza D, Contestabile P, et al. Lifecycle environmental impact assessment of an overtopping wave energy converter embedded in breakwater systems. Front Energy Res 2019;7.
[180] Têtu A, Fernandez Chozas J. A proposed guidance for the economic assessment of wave energy converters at early development stages. Energies 2021;14:4699.
[181] European Commission. A Clean Planet for all. A European strategic long-term vision for a prosperous, modern, competitive and climate neutral economy. COM; 2018. p. 25. 773 final. 2018.